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COMPRESSIVE BEHAVIOR OF TITANIUM ALLOY SKIN-STIFFENER SPECIMENS SELECTIVELY REINFORCED WITH BORON-ALUMINUM COMPOSITE

by Harvey W. Herring, Robert L. Carri, and Rosa C. Webster

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16. Abstract

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SUMMARY

A method of selectively reinforcing a conventional titanium airframe structure with unidirectional boron-aluminum composite attached by brazing has been successfully demonstrated in compression tests of short skin-stiffener specimens. In a comparison with all-titanium specimens, improvements in structural performance recorded for the composite-reinforced specimens exceeded 25 percent on an equivalent-weight basis over the range from room temperature to 700° K (800° F) in terms of both initial buckling and maximum strengths. Performance at room temperature was not affected by prior exposure at 588° K (600° F) for 1000 hours in air or by 400 thermal cycles between 219° K and 588° K (-65° F and 600° F). The experimental results were generally predictable from existing analytical procedures. No evidence of failure was observed in the braze between the boron-aluminum composite and the titanium alloy.

INTRODUCTION

Aluminum composite reinforced with boron filament (B-Al) is potentially useful for structural applications which involve service at elevated temperatures. However, the high cost of this material and the difficulties associated with joining and machining it are negative factors which currently prohibit its immediate, widespread use. These problems are largely circumvented by using composite strips as selective reinforcement applied to conventional metal airframe structure. This method of localized reinforcement yields a significant improvement in structural performance while requiring the minimum expenditure of composite material and fabrication effort. (See ref. 1.)

This paper reports the results of an effort to demonstrate the feasibility of selectively reinforcing a titanium airframe structure with thin strips of unidirectional B-Al composite attached by brazing. A number of riveted skin-stiffener specimens were fabricated both with and without composite reinforcement on the stiffener and were tested to failure in endwise compression. The objectives of the tests were to experimentally verify

the increased structural efficiency attainable with the reinforced specimens, specifically in the postbuckling region, and to demonstrate the structural integrity of the braze between composite and metal. Tests were conducted at temperatures up to 700° K (800° F) and after thermal cycling between 219° K and 588° K (-65° F and 600° F) and prolonged exposure for 1000 hours at 588° K (600° F). Experimentally determined values of buckling strength, maximum strength, and elastic modulus were compared with results predicted from existing analytical methods.

SYMBOLS

The units for physical quantities used in this paper are given in both the U.S. Customary Units and the International System of Units (SI). Measurements and calculations were made in U.S. Customary Units. Conversion factors relating the two systems are given in reference 2, and those pertinent to the present investigation are presented in the appendix.

A	cross-sectional area, meters^2 (inches^2)
b	element width, meters (inches)
b_a	width of skin between rivet lines, meters (inches)
E	modulus of elasticity, newtons/meter^2 (pounds-force/inch^2)
G	shear modulus, newtons/meter^2 (pounds-force/inch^2)
N	uniformly distributed load per unit width, newtons/meter (pounds-force/inch)
t	thickness, meters (inches)
t_e	titanium-weight-equivalent thickness, meters (inches)
t_{eq}	titanium-stiffness-equivalent thickness, meters (inches)
W	specimen width, meters (inches)
$\bar{\epsilon}$	average crippling strain
μ	Poisson's ratio

ρ	density, kilograms/meter^3 (pounds-mass/inch^3)
σ	stress or strength, newtons/meter^2 (pounds-force/inch^2)
σ_a	average stress in skin, newtons/meter^2 (pounds-force/inch^2)
σ_{cr}	buckling stress, newtons/meter^2 (pounds-force/inch^2)
σ_{cy}	compressive yield stress, newtons/meter^2 (pounds-force/inch^2)
$\bar{\sigma}$	average crippling stress, newtons/meter^2 (pounds-force/inch^2)

Subscripts:

c	composite
cal	calculated
cp	cap
cr	critical
eff	effective
exp	experimental
F	flexural
f	flange
L	direction parallel to filaments and direction of loading
max	maximum
s	secant
st	stiffener
T	direction transverse to filaments and direction of loading
Ti	annealed 6Al-4V titanium alloy

MATERIALS AND SPECIMENS

Skin-Stiffener Specimens

The basic specimen was a skin-stiffener combination, 25 cm (10 in.) long and 9.5 cm (3.7 in.) wide, fabricated from annealed 6Al-4V titanium alloy sheet 0.13 cm (0.051 in.) thick. (See fig. 1.) The single hat-section stiffener was brake formed from

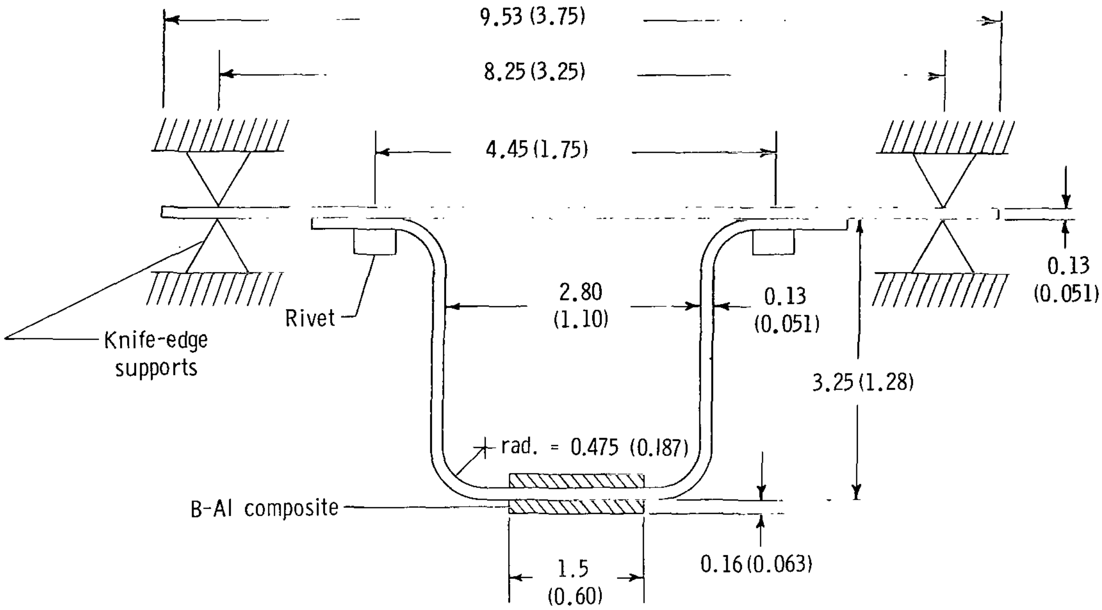

Figure 1.- Cross section of 6Al-4V titanium alloy skin-stiffener specimen reinforced with borón-aluminum (B-Al) composite. Dimensions are given in centimeters (inches).

sheet and fastened to the skin with 0.40-cm-diameter (0.16-in.) stainless-steel rivets countersunk flush with the outer skin surface. Twenty-three specimens were fabricated, nine of which were reinforced with B-Al strips, 0.16 cm (0.062 in.) thick and 1.5 cm (0.60 in.) wide, on both surfaces of the cap of the stiffener. The composite strips were brazed to the stiffeners in vacuum at 883° K (1130° F) by using 0.08-mm-thick (0.003-in.) 718 aluminum alloy foil as the filler. Sufficient pressure (about 170 kN/m^2 (25 psi)) was applied to the braze area to maintain contact between the strips, stiffener, and foils. The photograph in figure 2 shows part of the stiffener cross section after the composite had been added. Equal amounts of composite on opposite surfaces of the stiffener cap were used to minimize the warpage resulting from unequal thermal shrinkage during cooling from the brazing temperature. The skin-stiffener specimens were designed as short panels to insure a crippling mode of failure. They were intended solely to demonstrate the feasibility of selective reinforcement by using B-Al composite attached by brazing and do not represent an attempt at optimum design. Addition of the composite increased the weight of the specimens 8.8 percent.

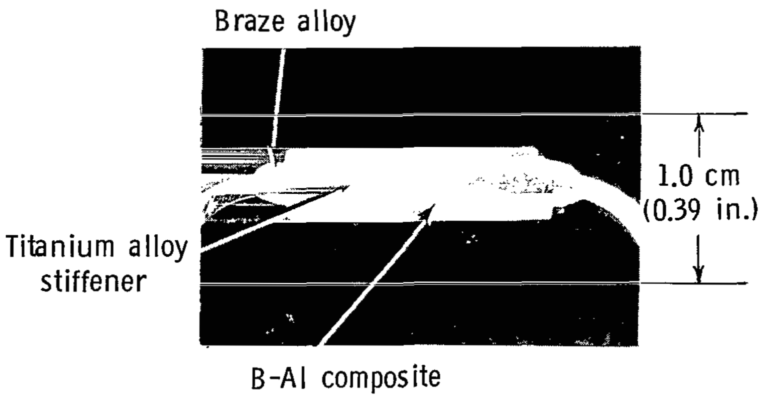

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Figure 2.- Reinforced stiffener cross section.

Two precautions were taken against bearing failure of the specimen ends. First, a titanium doubler, 2.5 cm (1.0 in.) wide and 0.13 cm (0.051 in.) thick, was riveted to the skins to increase the titanium bearing area. Second, the ends of all specimens were filled 2.5 cm (1.0 in.) back with a heat-resistant epoxy potting compound. The potting operation was considered necessary only to prevent brooming of the ends of the composite strips, but the ends of unreinforced specimens were also potted so that all specimens would be completely comparable. In figure 3 an unreinforced specimen with ends potted and doublers attached is shown before testing.

B-Al Composite Strips

The composite strips used in this study were made by winding 0.10-mm-diameter (0.004-in.) filament of silicon carbide coated boron onto a 0.03-mm-thick (0.001-in.) foil of 713 aluminum brazing alloy, and then plasma-spraying 6061 aluminum alloy into the filament array. The resulting composite monolayer was stacked and consolidated by heating above the melting temperature of the brazing alloy. The filament volume fraction was 0.46. Twenty such strips were purchased from a commercial vendor. Eighteen strips were used to reinforce skin-stiffener specimens, and two were taken at random for evaluation of composite mechanical and physical properties. For this purpose, strip segments 7.6 cm (3.0 in.) long were cut.

TEST METHODS

Skin-Stiffener Specimens

Twenty-three skin-stiffener specimens, nine of which were reinforced with B-Al composite, were loaded to failure in endwise compression. The edges of these specimens were supported with knife edges as indicated in figure 1. Deflection was measured by

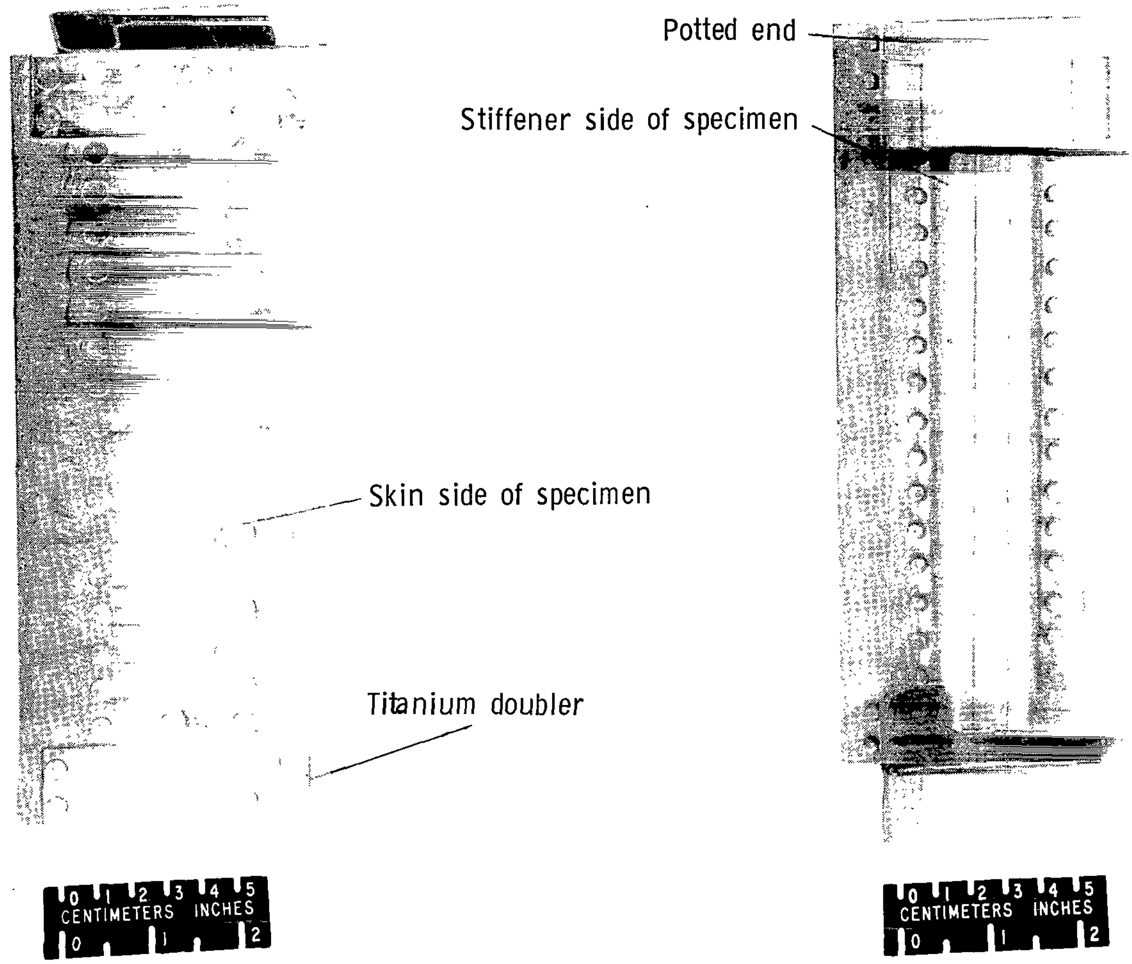

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Figure 3.- Unreinforced titanium skin-stiffener specimen before testing in compression.

using linearly variable differential transformers (LVDT's) which indicated relative motion between the upper and lower heads of the testing machine. At least two reinforced and two unreinforced specimens were tested at room temperature, 478° K (400° F), and 588° K (600° F). One reinforced and two unreinforced specimens were tested at 700° K (800° F). All tests were conducted at a strain rate of approximately 0.001/min.

Tests at room temperature.- Foil-type strain gages were bonded to two reinforced and two unreinforced skin-stiffener specimens before testing at room temperature. For these specimens, output was recorded from the strain gages as well as the LVDT's. This additional instrumentation was included to obtain local strains, which are necessary to experimentally analyze the mode of failure. Strain-gage location and numerical identification are indicated in figure 4.

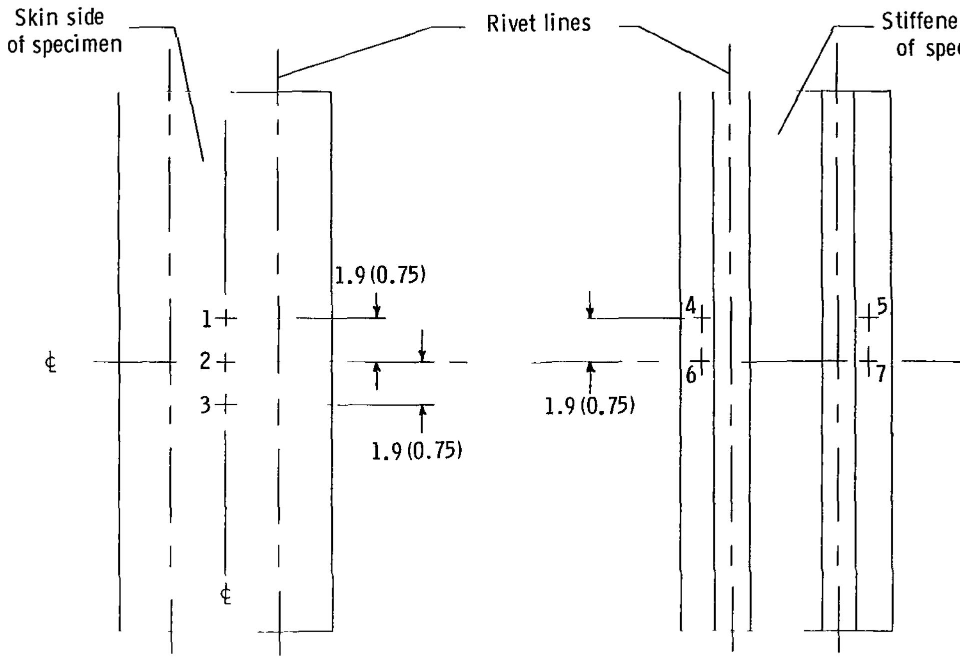

Figure 4.- Location and identification of strain gages used in tests of skin-stiffener specimens at room temperature. Dimensions are given in centimeters (inches).

Tests at elevated temperatures.- Specimen heating was accomplished by use of independently controlled arrays of incandescent quartz lamps. Typical temperature distributions during testing are shown in figures 5, 6, and 7 for the 478° K (400° F), 588° K (600° F), and 700° K (800° F) nominal test temperatures, respectively. Specimens were heated at an electronically controlled linear rate of 11° K/min (20° F/min), and there was a 5-minute hold between the time the test temperature was reached and the initial application of load. Strain was not measured for any of the specimens tested at elevated temperatures.

Exposure tests.- Two skin-stiffener specimens, one reinforced and one unreinforced, were exposed continuously for 1000 hours at 588° K (600° F) in air at sea-level atmospheric pressure before testing at room temperature. A second pair of specimens was subjected to 400 thermal cycles between 219° K and 588° K (-65° F and 600° F) in air before testing at room temperature. A single cycle required 20 minutes — 15 minutes for cooling and 5 minutes for heating. The heating and cooling rates were not controlled and therefore were not linear. The extreme temperatures of the cycle were indicated by a thermocouple attached to the specimens at the center of the skin. The specimens were alternately inserted into a cold chamber at 77° K (-320° F) and a hot chamber at 810° K (1000° F). They were withdrawn instantly when the extreme temperatures of the cycle were reached. There was no soaking period, and the specimens never reached equilibrium at either of the extreme temperatures.

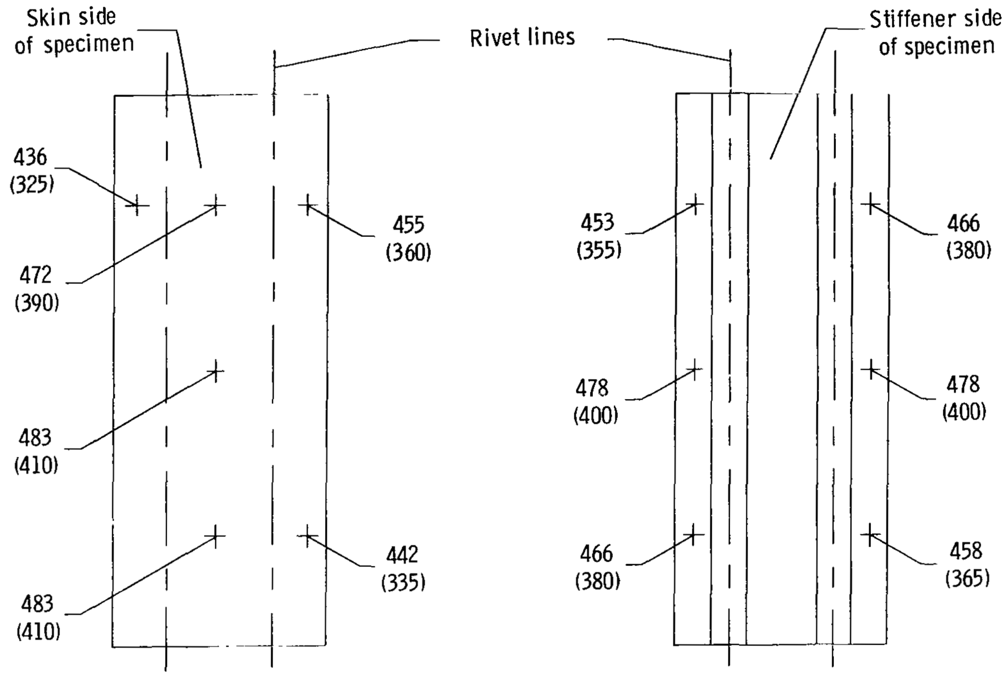

Figure 5.- Surface temperature distribution for skin-stiffener specimens tested at nominal temperature of 478° K (400° F). Values are given in degrees Kelvin (degrees Fahrenheit).

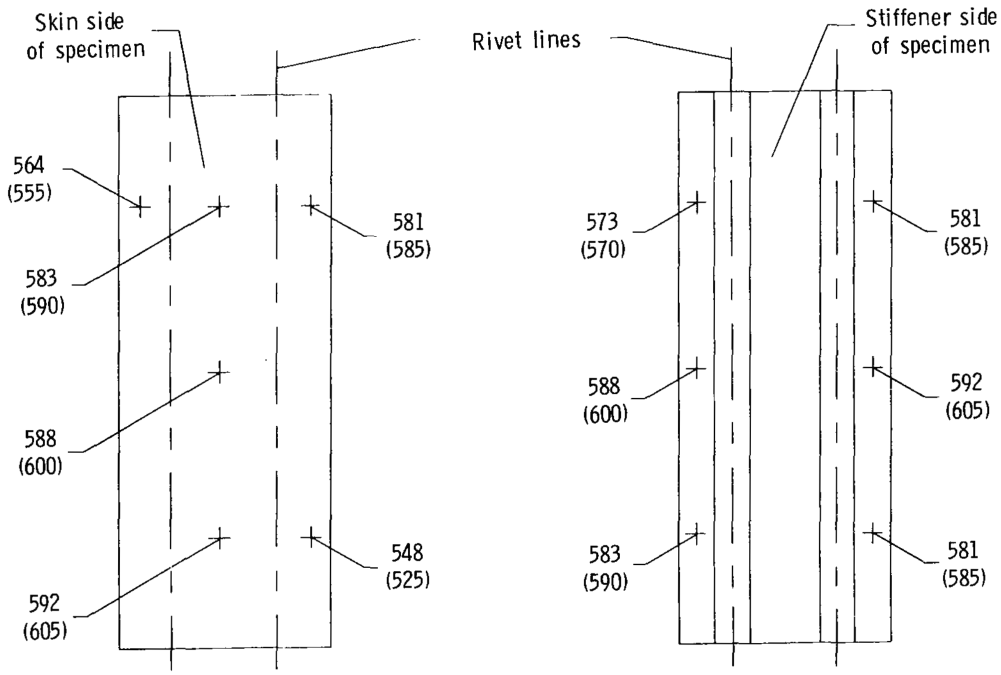

Figure 6.- Surface temperature distribution for skin-stiffener specimens tested at nominal temperature of 588° K (600° F). Values are given in degrees Kelvin (degrees Fahrenheit).

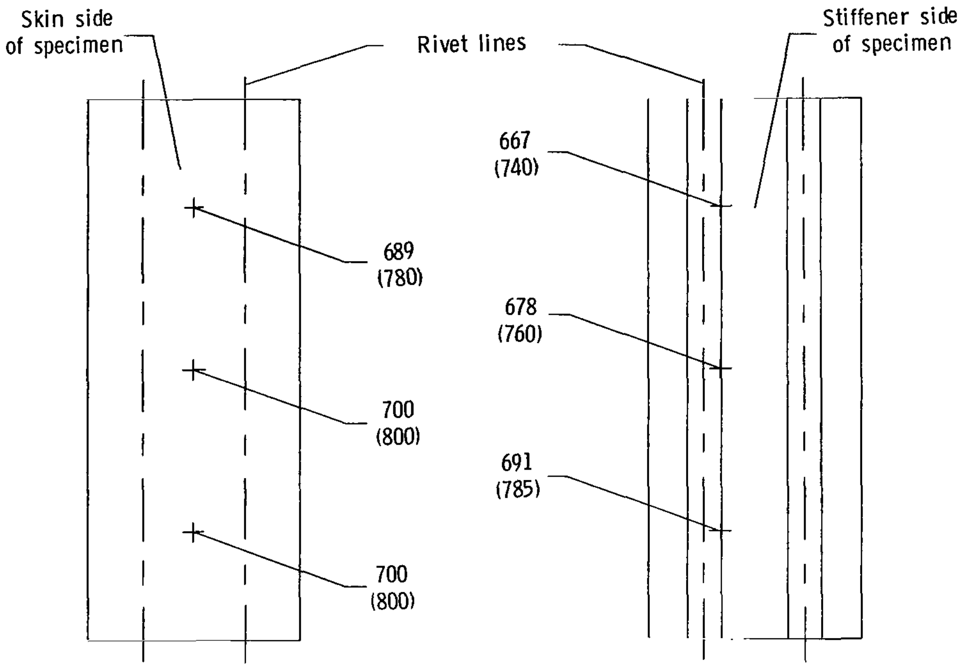

Figure 7.- Surface temperature distribution for skin-stiffener specimens tested at nominal temperature of 700° K (800° F). Values are given in degrees Kelvin (degrees Fahrenheit).

B-Al Composite Strips

Six strip segments were cut from the two randomly taken strips for characterization of the B-Al composite material used in this investigation. The nominal dimensions of these segments were 7.6 by 1.5 by 0.15 cm (3.0 by 0.60 by 0.06 in.). The segments were tested to failure in three-point bending over a span of 5.1 cm (2.0 in.). Deflection was measured by use of a dial gage which indicated relative motion between the two heads of the testing machine. Three segments were tested at room temperature, one at 478° K (400° F), and two at 588° K (600° F). Density was determined from weights and measurements obtained directly from fragments of the strip segments which were failed in the bend tests. Constituent volume fractions were determined by using those weights and measurements along with the weight of filaments remaining after dissolution of the matrix in a warm solution of sodium hydroxide.

TEST RESULTS

Skin-Stiffener Specimens

Data were obtained from all tests of skin-stiffener specimens in the form of load-shortening curves. Typical curves are presented in figure 8 for unreinforced specimens and in figure 9 for reinforced specimens. Curves are presented for tests conducted at

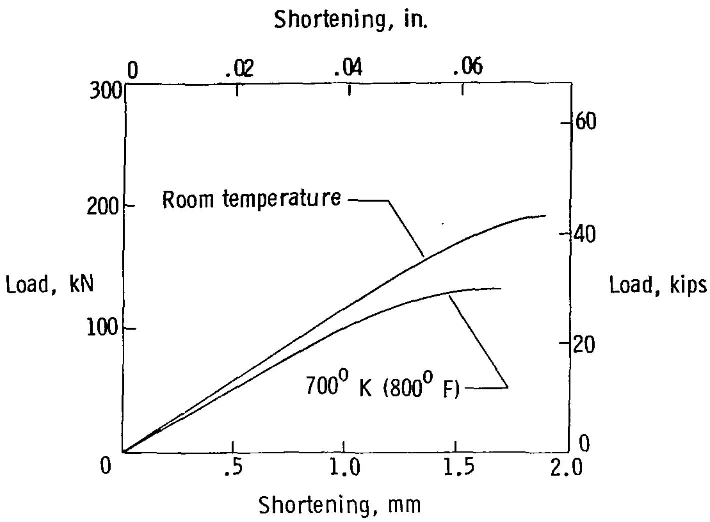

Figure 8.- Typical load-shortening curves from compression tests of unreinforced titanium skin-stiffener specimens. Cross-sectional area is 2.64 cm^2 (0.410 in^2).

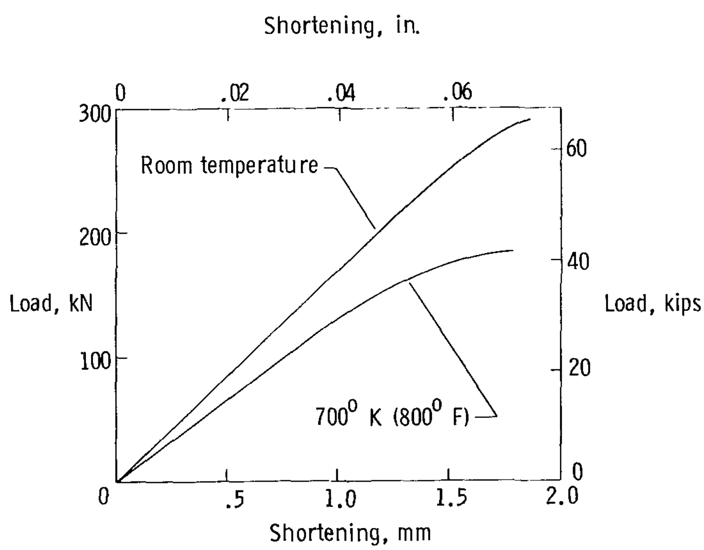

Figure 9.- Typical load-shortening curves from compression tests of reinforced titanium skin-stiffener specimens. Cross-sectional area is 3.14 cm^2 (0.486 in^2).

room temperature and at 700° K (800° F) to illustrate the decline in strength and stiffness observed at the extreme test temperature. The elastic modulus of a given specimen is related to the slope of the linear part of its load-shortening curve. The initial deviation from linearity represents the onset of local elastic buckling in the skin. Failure of the specimen occurs at the indicated maximum load by crippling of the stiffener and effective skin. Typical strain-gage data from tests at room temperature are plotted as load-strain curves in figure 10 for an unreinforced skin-stiffener specimen and in figure 11 for

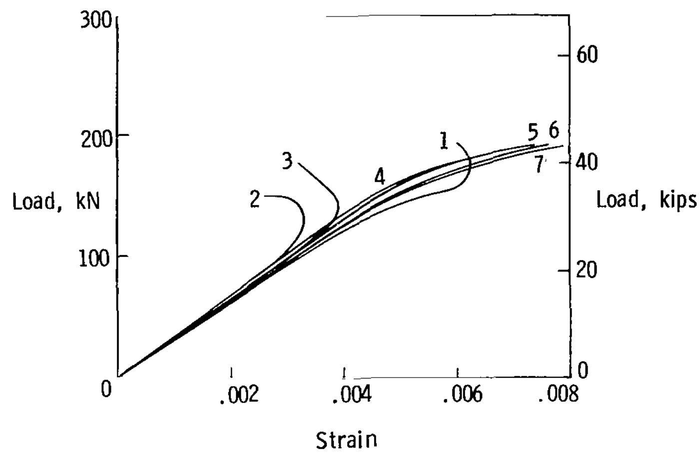

Figure 10.- Typical load-strain curves from compression tests of unreinforced titanium skin-stiffener specimens at room temperature. Numbers refer to strain-gage locations shown in figure 4. Cross-sectional area is 2.64 cm^2 (0.410 in^2).

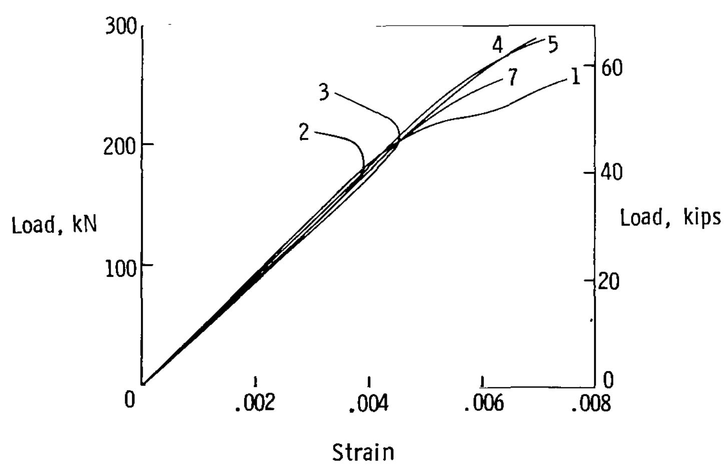

Figure 11.- Typical load-strain curves from compression tests of reinforced titanium skin-stiffener specimens at room temperature. Numbers refer to strain-gage locations shown in figure 4. Gage 6 was defective in this test. Cross-sectional area is 3.14 cm^2 (0.486 in^2).

a reinforced specimen. Elastic modulus, buckling strength, and maximum strength are presented in table I for unreinforced specimens. Similar results for reinforced specimens are given in table II. Several experimental values of elastic modulus were considered inaccurate because of rotation of one of the heads of the testing machine while the specimens were being loaded. These results have been omitted from both tabulations. Photographs showing the failure mode for a typical composite-reinforced specimen are presented in figures 12 and 13. In no case was there evidence of failure in the braze between the composite and the stiffener.

B-Al Composite Strips

Flexural tests of six strip segments yielded the average strengths and moduli listed in table III as experimentally determined values. Both strips selected for characterization contained a filament volume fraction of 0.46, but one strip was only about 94-percent dense. Variation in strength between strips was significant, and the observed values were generally lower than had been anticipated. A magnified cross section of the porous strip is shown in figure 14.

THEORETICAL ANALYSIS

Buckling strength, maximum strength, and elastic modulus were calculated for each skin-stiffener specimen by use of existing analytical procedures. Thermal stresses were not considered in the analysis. Calculated results are presented in table I for unreinforced specimens and in table II for reinforced specimens. Material properties used in the theoretical analysis are listed in table III. Values of E_L were not readily available for the B-Al composite at 588° K (600° F) and 700° K (800° F). The 588° K (600° F) value was calculated by assuming that the ratio of E_L to E_F at room temperature remains constant up to 588° K (600° F). The 700° K (800° F) value was obtained by linear extrapolation, since a value of E_F was not available at that temperature.

Buckling Strength

The buckling strength for all specimens was obtained by using the analysis of reference 3, a computerized analysis which makes use of minimum-energy principles to obtain the critical buckling loads of stiffened panels composed of orthotropic laminated elements. The model specimen configuration required by the analysis is shown as a schematic cross section in figure 15. The model is divided into discrete elements which are bounded in two dimensions by the nodal points 1 to 10. Coordinates of the nodes in the X-Y plane, with node 1 as the origin, are listed in table IV based on nominal dimensions of the actual specimen used in this investigation.

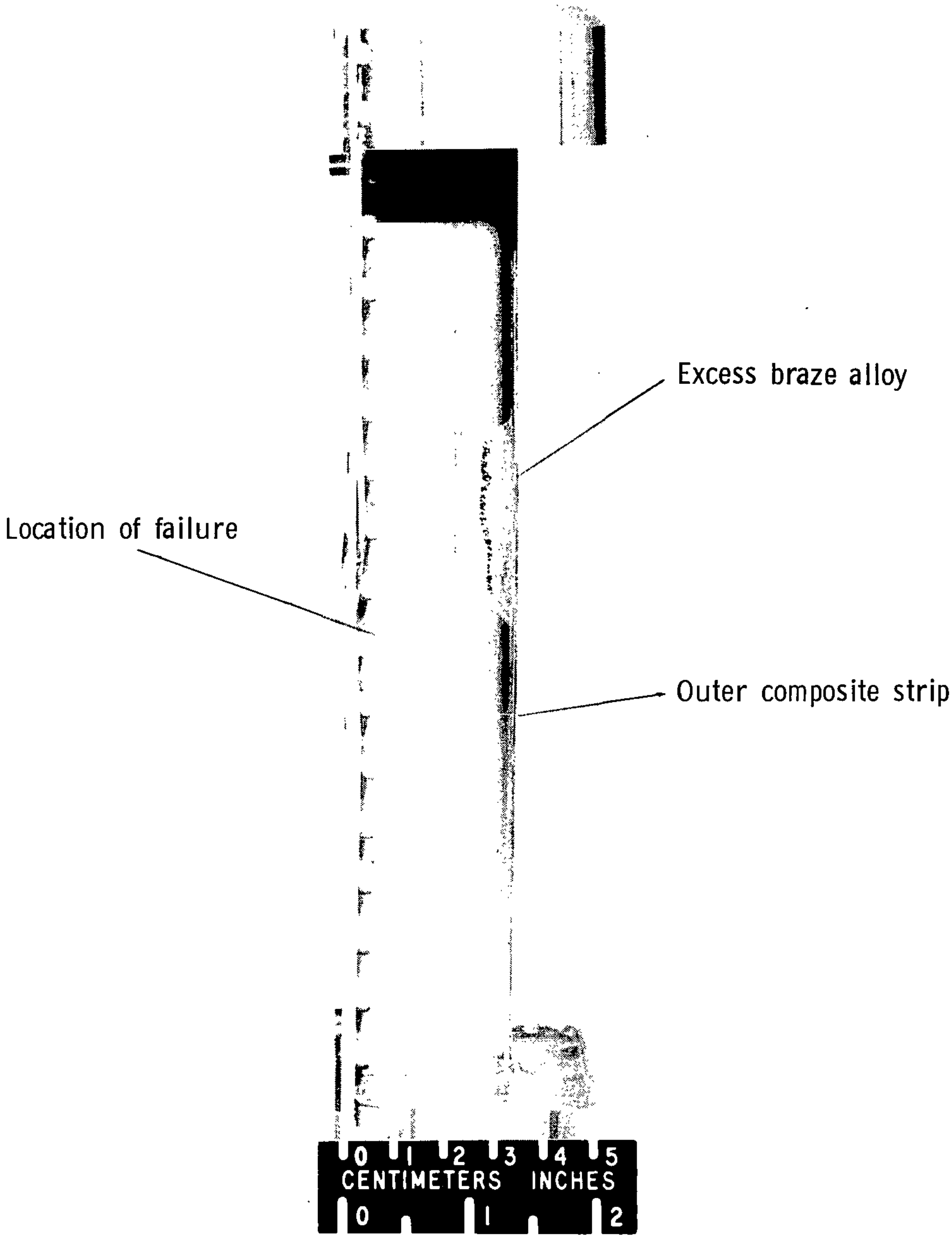

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Figure 12.- Crippling failure of composite-reinforced titanium skin-stiffener specimen.

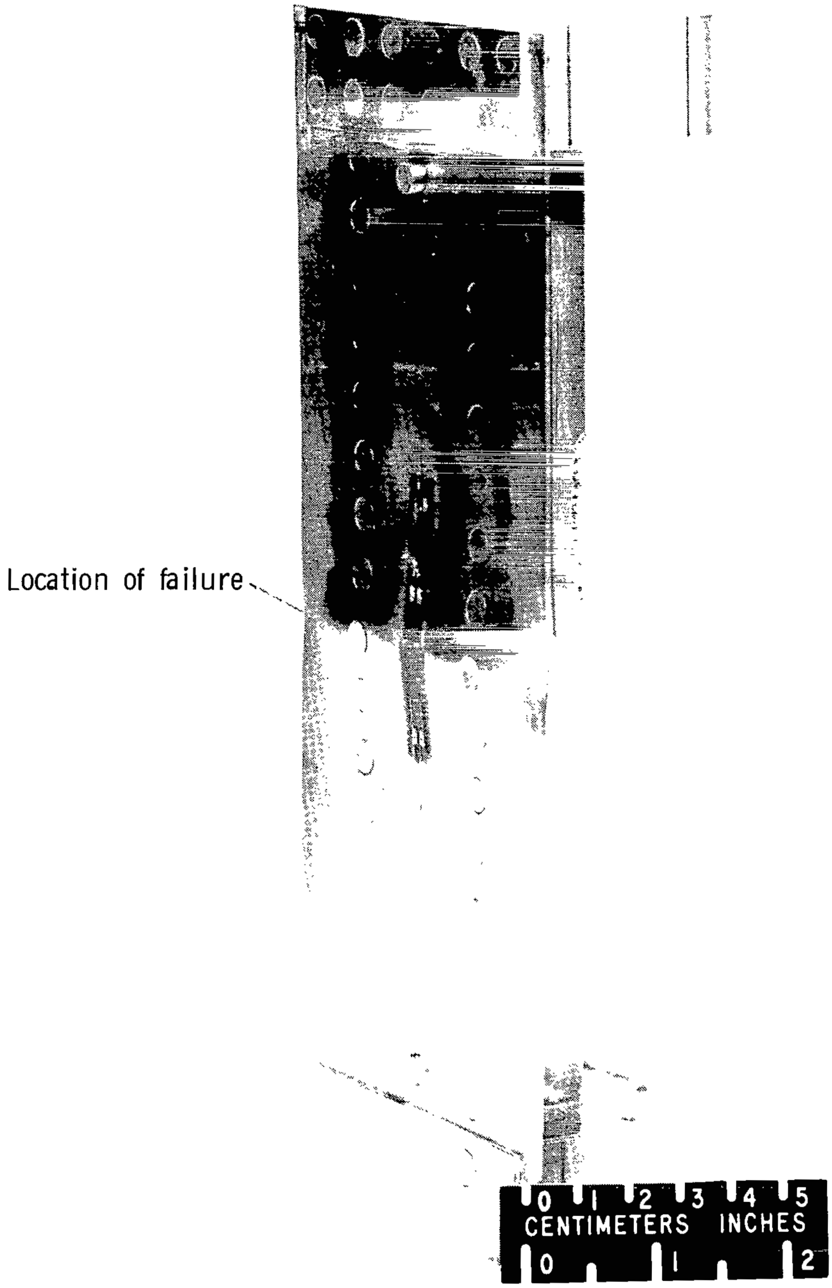

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Figure 13.- Extension of crippling failure across rivet line in skin of composite-reinforced titanium skin-stiffener specimen.

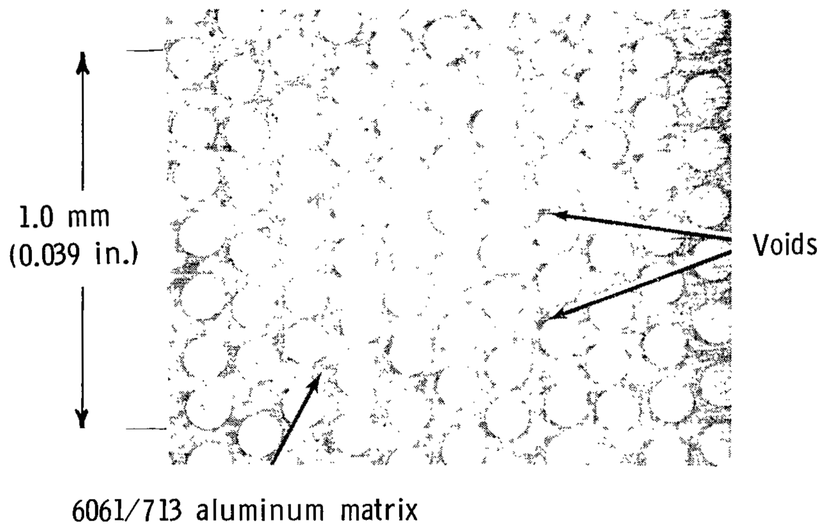

Figure 14.- Cross section of strip of boron-aluminum composite.

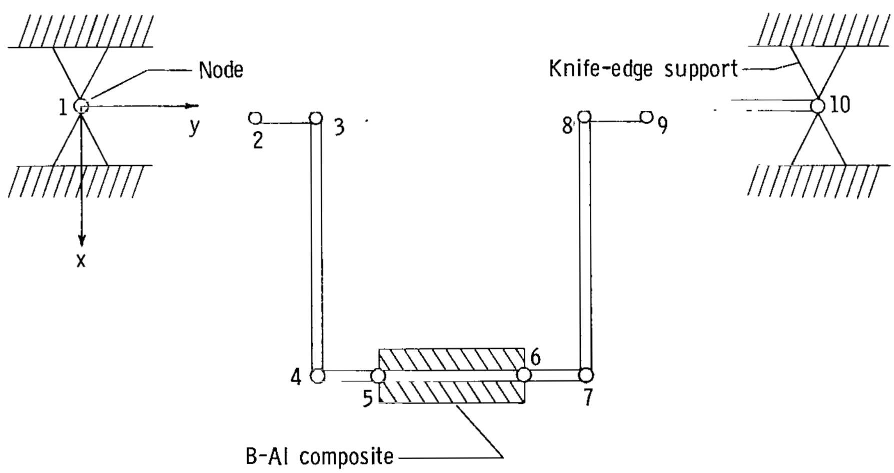

Figure 15.- Model skin-stiffener specimen idealization for analytical determination of buckling strengths.

The analysis indicated that both the reinforced and the unreinforced skin-stiffener specimens would exhibit initial instability in the form of local buckling of the skin between stiffener attachment lines. This instability was predicted to occur at approximately the same strain level in the skins of the different specimens. The local-buckling coefficient for this element of skin was calculated to be 5.80 on the basis of the results of the computer analysis. The analysis assumed simply supported boundary conditions for the loaded edges. However, for the specimen configuration used in this investigation, there was no significant difference between the buckling coefficients for loaded edges simply supported and loaded edges clamped. The value of 5.80 fell between the classical buckling-coefficient values of 4.0 for unloaded edges simply supported and 6.98 for unloaded edges clamped. The prospect of a wrinkling mode of instability resulting from the large rivet offset was investigated by using the method of reference 4 and was found to be remote.

Maximum Strength

At the onset of local buckling, the average stress through the skin thickness is redistributed, with peaks occurring at the stiffener attachment lines. When the peak stress approaches the failing stress of the stiffener (the crippling stress for the specimens in this investigation), the specimen can support no additional load. Thus, the maximum strength of the skin-stiffener specimen may be written as

$$\sigma_{max} = \frac{(\bar{\sigma}A)_{st} + (\sigma A)_c + \sigma_a Wt}{A_{st} + A_c + Wt} \tag{1}$$

The stiffener crippling stress $\bar{\sigma}_{st}$ is obtained by using a conventional stress analysis in which two basic flat-plate elements are defined – one unloaded edge free (flanges) and no unloaded edges free (webs). For this calculation the attached flange (unloaded edge free) width is assumed to be equal to the distance from the center line of the web to the outer edge of the rivet. The crippling stress of a section composed of such elements may be calculated as follows according to the method given in reference 5:

$$\bar{\sigma}_{st} = \frac{\sum A_{cp}\bar{\sigma}_{cp} + \sum A_f\bar{\sigma}_f}{\sum A_{cp} + \sum A_f} \tag{2}$$

For those specimens having composite reinforcement, a stiffness equivalent thickness for the cap of the hat-section stiffener was used in the crippling analysis. This thickness was determined from the relation

$$\left(t_{eq}\right)_{cp} = \frac{A_c\left(E_L\right)_c}{b_{cp}E_{Ti}} \tag{3}$$

The composite stress at the failing load was assumed to be proportional to the average crippling strain of the stiffener according to

$$\sigma_c = \bar{\epsilon}_{st}E_c \tag{4}$$

which is valid when the size and shape of the stiffener are such that the buckling and crippling stresses are identical. This was the case for the specimens used in this investigation.

The average stress in the skin at specimen failure is given by

$$\sigma_a = \frac{\left[\left(W - b_a\right) + b_{eff}\right]\bar{\sigma}_{st}}{W} \tag{5}$$

where $\left(W - b_a\right) + b_{eff}$ is the width from the attachment lines to each free edge of the specimen (fig. 1) added to the width of effective skin.

Substituting the basic Von Karman equation (ref. 6)

$$b_{eff} = 1.9t\sqrt{\frac{E_s}{\bar{\sigma}_{st}}} \tag{6}$$

into equation (5) results in

$$\sigma_a = \frac{\left(W - b_a\right)\bar{\sigma}_{st} + 1.9t\sqrt{E_s\bar{\sigma}_{st}}}{W} \tag{7}$$

Elastic Modulus

Calculated values of elastic moduli listed in tables I and II were obtained from the rule-of-mixtures relationship

$$E_{cal} = \frac{(EA)_{Ti} + (EA)_c}{A_{Ti} + A_c} \tag{8}$$

DISCUSSION

Skin-Stiffener Specimens

Buckling strength.- Experimental and calculated buckling strengths are compared in figure 16 over the entire range of test temperatures. The comparison is made for both

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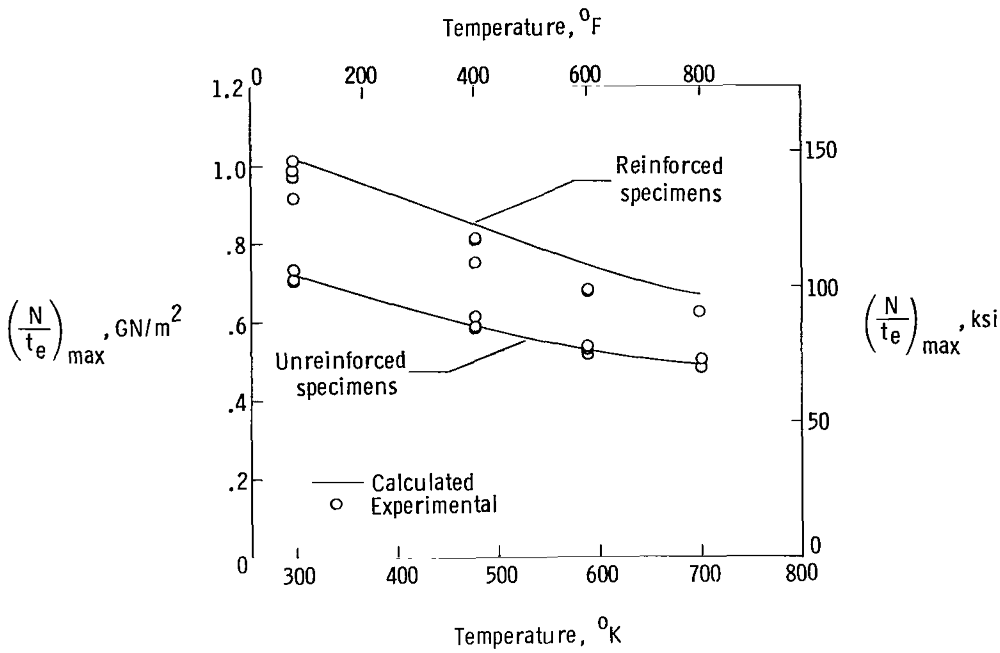


Figure 17.- Comparison of titanium-weight-equivalent maximum strengths of reinforced and unreinforced skin-stiffener specimens on basis of temperature.

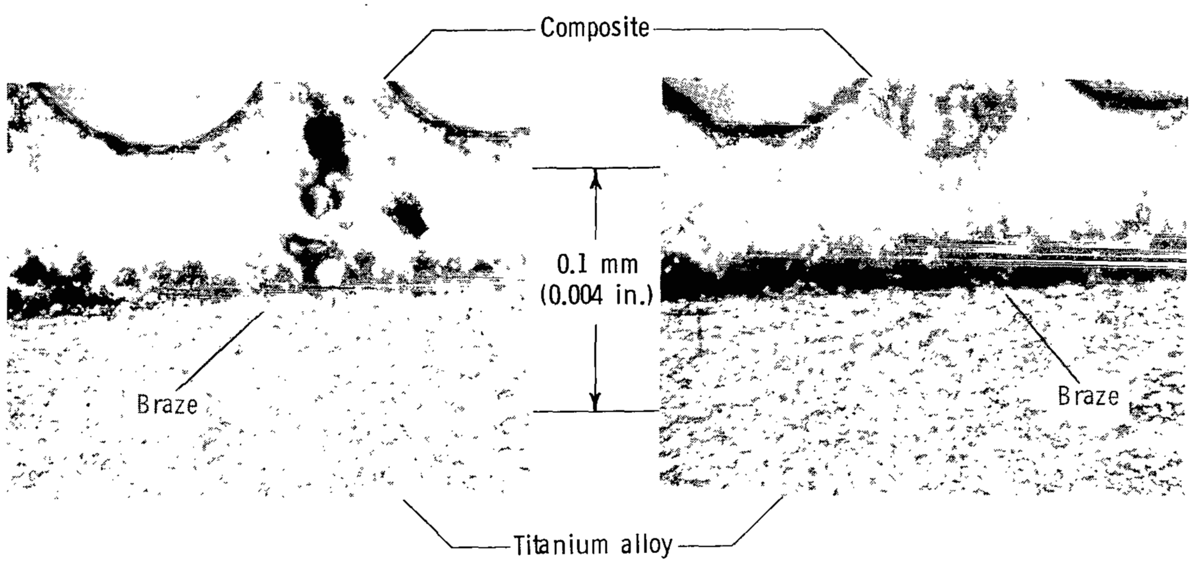
strength. The improvement gained by adding the composite strips ranges from about 35 percent at room temperature to 25 percent at 700° K (800° F), again on an equivalent-weight basis.

Elastic modulus.- Some difficulty in determining elastic modulus was encountered early in the test program because of rotation of one of the heads of the testing machine. By the time this problem was corrected, many of the available skin-stiffener specimens had been failed, and measurement of an accurate value of elastic modulus was impossible. However, the calculated values listed in tables I and II appear to be reasonable, and a comparison of these tables shows an increase resulting from the addition of composite reinforcement. The improvement was predictable on the basis of a rule-of-mixtures calculation.

Effects of exposure.- Two skin-stiffener specimens, one reinforced and one unreinforced, were exposed in air for 1000 hours at 588° K (600° F). A second pair of specimens was subjected to 400 thermal cycles between 219° K and 588° K (-65° F and 600° F). All four specimens were subsequently loaded to failure at room temperature. The results (tables I and II) were identical to those observed for specimens which had not been exposed. Neither the prolonged nor the cyclic exposure had an apparent effect on the structural performance of the few skin-stiffener specimens tested.

Effects of material properties.- Results of the limited number of flexural tests conducted indicated that the strength of the B-Al composite used to reinforce the skin-stiffener specimens was relatively low. One of the more important results of this investigation, therefore, was the observation that the concept of selective reinforcement with composites allows material with relatively poor tensile strength to be used in a purely compressive loading situation where relatively high stresses are readily withstood. In no case was failure of the composite strips observed in advance of overall failure of a skin-stiffener specimen.

Integrity of the braze.- The braze between the B-Al composite and the titanium alloy stiffeners proved to be completely satisfactory. No evidence of braze failure was observed under any of the test conditions. Magnified views of the braze cross section are shown in figure 18 for the as-fabricated condition and after 1250 hours of exposure



(a) As fabricated.

(b) After 1250 hours of exposure at 588° K (600° F) in air.

Figure 18.- Cross sections of braze between B-Al composite and titanium stiffener. Keller's etch.

at 588° K (600° F). Even after prolonged exposure, the braze line is well defined on the titanium side with minimal penetration into the stiffener.

It is interesting to note that all brazing was inadvertently done about 28° K (50° F) higher than recommended by the manufacturer of the brazing alloy. In fact, the brazing temperature was sufficiently high that some melting of the composite matrix may have occurred. In spite of the error, a significant improvement in structural performance of

the skin-stiffener specimens was realized through the addition of composite reinforcement. This result suggests that a certain degree of leniency is inherent in the brazing method of attachment. This would be a definitely favorable feature in any consideration of the future use of the method.

CONCLUDING REMARKS

A method of selectively reinforcing conventional titanium airframe structure with unidirectional boron-aluminum composite attached by brazing has been successfully demonstrated in compression tests of short skin-stiffener specimens. In a comparison with all-titanium specimens, improvements in structural performance recorded for the composite-reinforced specimens exceeded 25 percent on an equivalent-weight basis over the range from room temperature to 700° K (800° F) in terms of both initial buckling and maximum strengths. Performance at room temperature was not affected by prior exposure at 588° K (600° F) for 1000 hours in air or by 400 thermal cycles between 219° K and 588° K (-65° F and 600° F). The experimental results were generally predictable from existing analytical procedures. No evidence of failure was observed in the braze between the boron-aluminum composite and the titanium.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 27, 1971.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12. (See ref. 2.) Conversion factors for the units used herein are given in the following tables:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Area	in^2	6.452×10^{-4}	square meters (m^2)
Density	lbm/in^3	2.768×10^{4}	kilograms per cubic meter (kg/m^3)
Force	kip = 1000 lbf	4.448×10^{3}	newtons (N)
Length	in.	2.54×10^{-2}	meters (m)
Moduli and stress	ksi = 1000 lbf/in^2	6.895×10^{6}	newtons per square meter (N/m^2)
Pressure	psi = lbf/in^2	6.895×10^{3}	newtons per square meter (N/m^2)
Temperature	(^{o}F + 459.67)	5/9	degrees Kelvin (^{o}K)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiple of units are as follows:

Prefix	Multiple
milli (m)	10^{-3}
centi (c)	10^{-2}
kilo (k)	10^{3}
giga (G)	10^{9}

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TABLE I.- EXPERIMENTAL AND CALCULATED RESULTS FOR COMPRESSION TESTS OF UNREINFORCED TITANIUM SKIN-STIFFENER SPECIMENS

Specimen	Test temperature		$(\sigma_{cr})_{exp}$		$(\sigma_{cr})_{cal}$		$(\sigma_{max})_{exp}$		$(\sigma_{max})_{cal}$		E_{exp}		E_{cal}	
	°K	°F	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi
1	298	75	0.504	73.1	0.502	72.8	0.731	106	0.704	102	114	16 500	113	16 400
2			.503	73.0			.731	106			---	-----		
3			.492	71.3			.711	103			115	16 600		
4			.480	69.5			.711	103			118	17 100		
[a]5			.503	73.0			.725	105			---	-----		
[b]6			.519	75.2			.739	107			---	-----		
7	478	400	0.445	64.5	0.443	64.3	0.588	85.2	0.586	84.9	---	-----	100	14 500
8			.432	62.6			.615	89.0			---	-----		
9			.456	66.0			.594	86.1			---	-----		
10	588	600	0.383	55.5	0.413	59.9	0.521	75.5	0.532	77.1	97	14 000	93	13 500
11			.452	65.5			.538	78.0			---	-----		
12			.403	58.5			.531	77.0			---	-----		
13	700	800	0.336	48.7	0.371	53.7	0.500	72.5	0.482	69.8	---	-----	84	12 100
14	700	800	.326	47.2	.371	53.7	.483	70.0	.482	69.8	90	13 000	84	12 100

[a] Tested after 400 thermal cycles between 219° K and 588° K (-65° F and 600° F) in air at sea-level atmospheric pressure.

[b] Tested after 1000 hours of continuous exposure at 588° K (600° F).

TABLE II.- EXPERIMENTAL AND CALCULATED RESULTS FOR COMPRESSION TESTS OF REINFORCED TITANIUM SKIN-STIFFENER SPECIMENS

Specimen	Test temperature		$(\sigma_{cr})_{exp}$		$(\sigma_{cr})_{cal}$		$(\sigma_{max})_{exp}$		$(\sigma_{max})_{cal}$		E_{exp}		E_{cal}	
	°K	°F	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi	GN/m^2	ksi
15	298	75	0.604	87.5	0.569	82.4	0.931	135	0.959	139	130	18 800	130	18 800
16			.638	92.5			.953	138			130	18 800		
[a]17			.569	82.5			.870	126			128	18 500		
[b]18			.601	87.0			.918	133			130	18 800		
19	478	400	0.528	76.5	0.516	74.9	0.710	103	0.800	116	115	16 700	117	16 900
20	478	400	.516	74.8	.516	74.9	.773	112	.800	116	---	-----	117	16 900
21	588	600	0.462	66.9	0.464	67.3	0.639	92.6	0.704	102	---	-----	107	15 600
22	588	600	.499	72.3	.464	67.3	.638	92.4	.704	102	---	-----	107	15 600
23	700	800	0.421	61.0	0.412	59.7	0.593	86.0	0.627	90.9	101	14 700	96	14 000

[a] Tested after 400 thermal cycles between 219° K and 588° K (-65° F and 600° F) in air at sea-level atmospheric pressure.

[b] Tested after 1000 hours of continuous exposure at 588° K (600° F).

TABLE III. - MATERIAL PROPERTIES

Property	Temperature, °K (°F)			
	298 (75)	478 (400)	588 (600)	700 (800)
Aluminum alloy reinforced with boron filament				
[a] σ_F, GN/m^2 (ksi)	0.807 (117)	0.738 (107)	0.766 (111)	
[a] E_F, GN/m^2 (ksi)	187 (27 100)	186 (26 900)	154 (22 400)	
E_L, GN/m^2 (ksi)	[b] 221 (32 000)	[b] 216 (31 400)	[c] 184 (26 700)	[c] 152 (22 000)
E_T, GN/m^2 (ksi)	[b] 124 (18 000)			
G_{LT}, GN/m^2 (ksi)	[b] 41 (6000)			
μ_{LT}	[b] 0.23			
ρ, kg/m^3 (lbm/in^3)	[a] 2700 (0.097)			
Annealed 6Al-4V titanium alloy				
σ_{cy}, GN/m^2 (ksi)	0.952 (138)	0.745 (108)	0.65 (94)	0.60 (87)
E, GN/m^2 (ksi)	113 (16 400)	100 (14 500)	91.8 (13 300)	83.5 (12 100)
G, GN/m^2 (ksi)	43 (6200)	38 (5500)	3.53 (512)	3.16 (458)
ρ, kg/m^3 (lbm/in^3)	4400 (0.16)			

[a] Experimentally determined at NASA.
[b] Furnished by material supplier (experimentally determined).
[c] Calculated at NASA.

TABLE IV.- NODAL COORDINATES RELATING TEST SPECIMENS TO MODEL SPECIMEN CONFIGURATION USED IN ANALYTICAL DETERMINATION OF BUCKLING STRENGTHS

Node	Coordinates			
	y		x	
	cm	in.	cm	in.
1	0	0	0	0
2	1.91	.75	[a]0	[a]0
3	2.67	1.05	0	0
4	2.67	1.05	3.12	1.23
5	3.38	1.33	3.12	1.23
6	4.90	1.93	3.12	1.23
7	5.59	2.20	3.12	1.23
8	5.59	2.20	0	0
9	6.35	2.50	0	0
10	8.25	3.25	0	0

[a] Stiffener flanges are assumed to lie on the Y-axis.

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